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ARIZONA DEPARTMENT OF ENVIRONMENTAL QUALITY

Henry R. Darwin
Director

via e-mail

June 22, 2015
FPU15-274

Ms. Catherine Jerrard
AFCEC/CIBW
706 Hangar Road
Rome, NY 13441

RE: WAFB – *Hydraulic Containment During Steam Enhanced Extraction – A TEE Reference; ST012 Site, Mesa, AZ;* Praxis document dated June 22, 2015

Dear Ms. Jerrard:

Arizona Department of Environmental Quality (ADEQ) Federal Projects Unit (FPU) and ADEQ contractors UXO Pro, Inc. and Praxis Environmental Technologies present this supplement document to *ADEQ Evaluation of USAF Response to ADEQ Comments; Weekly Progress Report April 27, 2015* and *Progress Report May 4, 2015*; *Steam Enhanced Extraction at the Former Williams AFB, ST012 Site, Mesa, AZ*; ADEQ document dated May 14, 2015. This document's purpose is to recall a method to estimate the steam zone heated soil volume as a time function. This method is within the Thermal Enhanced Extraction (TEE) Pilot Test Evaluation Report, Appendix I.

SUPPLEMENTAL INFORMATION

For hydraulic containment during steam injection, the following mass balance applies,

(Extraction Rate) > (Injection Rate + GW Encroachment + Steam-Displaced Groundwater)

$$\dot{m}_{extract} > \dot{m}_{inject} + \dot{m}_{encroach} + \dot{m}_{displace}$$

$$\frac{\dot{m}_{extract}}{\dot{m}_{inject} + \dot{m}_{encroach} + \dot{m}_{displace}} > 1$$

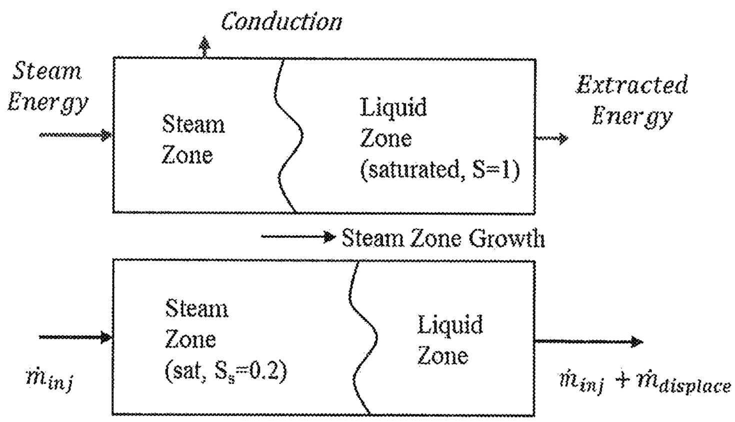
During simple water injection and extraction, hydraulic containment is identical for both a mass balance and a volume balance and no net displacement occurs. However, because of the phase change during steam injection, a volume/energy balance is required to assess hydraulic containment. This requirement is included in the expression above through the displacement term and can be estimated from the energy balance during steam injection as described below.

The TEE Pilot Test Evaluation Report, Appendix I, provided calculations in detail for estimating the volume of soil heated to a steam zone as a function of time. Use of the method is also provided in the TEE Pilot Study Work Plan, Appendix C. The model is a straightforward mass and energy balance described by numerous references over the last 50 years (e.g., Marx & Langenheim, 1959; Mandl & Volek, 1969; Menegus & Udell, 1985),

$$\frac{\Delta V}{\Delta t} = \frac{\dfrac{\dot{m}_{inj}}{\rho_w \varphi}\left[1 + \dfrac{h_{fg}}{c_{pw}(T_S - T_0)}\right]}{\dfrac{\rho_r c_{pr}(1-\varphi)}{\rho_w c_{pw}\varphi} + S_S + (1 - S_S)\dfrac{\rho_v}{\rho_w}\left[1 + \dfrac{h_{fg}}{c_{pw}(T_S - T_0)}\right]}$$

The energy balance for the steam zone can be related to the rate of water displacement through a water mass balance on the volume. For a given injection time, the steam zone volume grows and results in a change in the water mass as illustrated below,

$$\dot{m}_{inj} + \dot{m}_{displace} = \frac{\Delta V}{\Delta t}\rho_w \varphi (1 - S_S)$$



The model can also be modified to include the energy extraction rate and vertical heat conduction to confining layers (Yortsos, 1982),

$$\frac{\dot{m}_{inj} + \dot{m}_{displace}}{\rho_w \varphi (1 - S_S)} = \frac{\dfrac{\dot{m}_{inj}}{\rho_w \varphi}\left[1 + \dfrac{h_{fg}}{c_{pw}(T_S - T_0)}\right] - \dfrac{\dot{E}_{extraction}}{\rho_w \varphi c_{pw}(T_S - T_0)} - \dfrac{\dot{H}_{conduction}}{\rho_w \varphi c_{pw}(T_S - T_0)}}{\dfrac{\rho_r c_{pr}(1-\varphi)}{\rho_w c_{pw}\varphi} + S_S + (1 - S_S)\dfrac{\rho_v}{\rho_w}\left[1 + \dfrac{h_{fg}}{c_{pw}(T_S - T_0)}\right]}$$

The extraction rate of energy is readily measured and can be included simply as a fraction of the injected energy (F_{ext}). Similarly, the thermal conduction can be accounted for as a percentage reduction on the injection rate (F_{cond}). The vertical heat conduction is generally slow compared to the steam injection rate, as demonstrated by the current vertical temperature profiles for SEE and during the TEE Pilot Test,

$$\frac{\dot{m}_{inj} + \dot{m}_{displace}}{\rho_w \varphi (1 - S_S)} = \frac{\dfrac{\dot{m}_{inj}}{\rho_w \varphi}\left[1 + \dfrac{h_{fg}}{c_{pw}(T_S - T_0)}\right](1 - F_{ext} - F_{cond})}{\dfrac{\rho_r c_{pr}(1-\varphi)}{\rho_w c_{pw}\varphi} + S_S + (1 - S_S)\dfrac{\rho_v}{\rho_w}\left[1 + \dfrac{h_{fg}}{c_{pw}(T_S - T_0)}\right]}$$

Rearranging yields an expression for the water mass displaced as a function of the steam injection yields,

$$\frac{\dot{m}_{displace}}{\dot{m}_{inj}} = \frac{(1-S_S)\left[1+\frac{h_{fg}}{c_{pw}(T_S-T_0)}\right](1-F_{ext}-F_{cond})}{\frac{\rho_r c_{pr}(1-\varphi)}{\rho_w c_{pw}\varphi}+S_S+(1-S_S)\frac{\rho_v}{\rho_w}\left[1+\frac{h_{fg}}{c_{pw}(T_S-T_0)}\right]}-1$$

This expression provides a straightforward method for estimating the displacement rate of water during steam injection. Typical property values for steam injection in the LSZ are provided in the table below:

Parameter	T_s (266 °F)
Total Porosity (ϕ), nd	0.30
Solid/Rock Density (ρ_r), lb/ft³	165.5
Solid/Rock Heat Capacity (c_{pr}), BTU/lb/°F	0.24
Water Density (ρ_w), lb/ft³	58.34
Water Heat Capacity (c_{pw}), BTU/lb/°F	1.02
Steam Vapor Density (ρ_v), lb/ft³	0.094
Steam Enthalpy of Vaporization (h_{fg}), BTU/lb	934

Substituting these values with an ambient temperature of 82°F (based on SEE data) yields,

$$\frac{\dot{m}_{displace}}{\dot{m}_{inj}} = \frac{(1-0.20)\left[1+\frac{934}{1.02(266-82)}\right](1-F_{ext}-F_{cond})}{\frac{(165.5)(0.24)(1-0.30)}{(58.34)(1.02)(0.30)}+0.20+(1-0.20)\frac{0.094}{58.34}\left[1+\frac{934}{1.02(266-82)}\right]}-1$$

$$\frac{\dot{m}_{displace}}{\dot{m}_{inj}} = (3.0)(1-F_{ext}-F_{cond})-1 = 2.0-3(F_{ext}+F_{cond})$$

$$\frac{\dot{m}_{displace}}{\dot{m}_{inj}} = 2.0-3(F_{ext}+F_{cond})$$

Substituting LSZ-specific values into the original requirement for hydraulic containment yields,

$$\frac{\dot{m}_{extract}}{\dot{m}_{inj}+\dot{m}_{encroach}+\dot{m}_{displace}} = \frac{\dot{m}_{extract}}{\dot{m}_{inj}+\dot{m}_{encr}+\ \dot{m}_{inj}[2-3(F_{ext}+F_{cond})]} > 1$$

As an example, consider the initial injection period when no extraction of energy is occurring (F_{ext}=0) and conservatively neglect heat conduction (F_{cond}=0),

$$\frac{\dot{m}_{extract}}{\dot{m}_{inject}+\dot{m}_{encroach}+2\,\dot{m}_{inject}} > 1$$

Under these conditions, the displacement rate is double the injection rate and hydraulic containment requires an extraction rate triple that of the injection rate as a minimum without considering encroachment.

The energy for thermal conduction is the result of steam condensation and results in condensate within the steam zone that must be displaced by the flowing steam. Hence, the fraction of energy for conduction is inherently limited. Based on the energy balances in the TEE Pilot Test and the temperature profiles measured during SEE, a generous assumption for the average fraction of injected energy used for thermal conduction of fine-grained soils is 20% (F_{con}=0.2). Substituting this value yields,

$$\frac{\dot{m}_{extract}}{\dot{m}_{inj} + \dot{m}_{encr} + \dot{m}_{inj}[1.4 - 3F_{ext}]} > 1$$

Extraction rates are provided in Figure 17. The injection rate of energy (as steam) and the extraction rate of energy are available in Figure 21 of the Weekly Progress Reports to calculate the fraction of energy extracted such that hydraulic containment can be assessed on a weekly basis. However, separate measures of energy extraction from the LSZ and UWBZ are not available and the fractions are assumed equal.

Data from weekly progress reports were used as input into the mass ratio expression above. Separate calculations for the LSZ and UWBZ were performed with data and parameters approximated from Figures 17 and 21. The parameters and results are provided below. As indicated, hydraulic containment has not been maintained during any of the select operating conditions shown below. On 6/1/15, the total extraction rate required to achieve a net ratio of 1.5 in the LSZ was about 120 gpm (205 gpm overall) and in 6/8/15 the rate needed to be about 150 gpm (275 gpm overall) for the reported steam injection rates.

Select hydraulic containment mass and energy balance operating conditions are provide on Table 1 [*TABLE 1: Mass & Energy Balances for Hydraulic Containment*]. Table 1 is presented on the following page.

TABLE 1: Mass & Energy Balances for Hydraulic Containment

Week	Extraction $\dot{m}_{extract}$	Injection $\dot{m}_{inject}$	GW Flow $\dot{m}_{encroach}$	F_{ext} $\dot{E}_{ext}/\dot{E}_{inj}$	Displace $\dot{m}_{displace}$	Net Ratio
OVERALL	(incl CZ ext)					
11/23/14	126	66	12	0.05	82	**0.79**
12/1/14	129	65	12	0.08	75	**0.85**
12/8/14	161	72	12	0.07	85	**0.78**
12/15/14	142	75	12	0.09	86	**0.82**
6/1/2015	120	73	12	0.40	36	**1.00**
6/8/2015	101	70	12	0.25	66	**0.68**
LSZ						
11/23/14	82	66	7.5	0.05	82	**0.53**
12/1/14	81	65	7.5	0.08	75	**0.55**
12/8/14	85	64	7.5	0.09	72	**0.59**
12/15/14	96	61	7.5	0.11	66	**0.72**
6/1/2015	70	49	7.8	~0.40	24	**0.86**
6/8/2015	55	48	7.8	~0.25	45	**0.55**
UWBZ						
12/8/14	28	15	4.2	0.00	21	**0.70**
12/15/14	31	14	4.2	0.00	20	**0.79**
6/1/2015	41	23	4.2	~0.40	11	**1.06**
6/8/2015	38	23	4.2	~0.25	21	**0.79**

Values listed are in gallons per minute equivalent based on a water density of 8.35 lbs/gallon
$\dot{m}_{displace} = \dot{m}_{inj}[1.4 - 3F_{ext}]$ for 20% conduction during early steam injection
$\dot{m}_{displace} = \dot{m}_{inj}[1.7 - 3F_{ext}]$ for 10% conduction at later times when clays are heated

Closure

Thank you for the opportunity to evaluate your responses. Should you have any questions regarding this correspondence, please contact me by phone at (602) 771-4121 or e-mail miller.wayne@azdeq.gov.

Sincerely,

Wayne Miller

Wayne Miller
ADEQ Project Manager
Federal Projects Unit
Remedial Projects Section
Waste Programs Division

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